# THE USE OF METEOROLOGICAL SATELLITES FOR DISCERNING MARINE FOG

Richard Thomas Wallace

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# THESIS

THE USE OF METEOROLOGICAL SATELLITES FOR DISCERNING MARINE FOG

by

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## ABSTRACT

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# I. INTRODUCTION

## A. BACKGROUND

Marine fog is an ever-present menace to both commercial and military shipping. The ship master and ship owner are threatened with costly schedule delays and losses of property and personnel because of the possibility of collision during periods of low visibility in marine fog. Likewise, military naval forces afloat and naval air forces are hampered by fog during evolutions requiring unrestricted or near-unrestricted visibility. For example, aircraft carrier flight operations (launch and recovery), antisubmarine warfare maneuvers (ship based and shore based), tactical air-strike operations, and underway replenishment, all require unimpaired horizontal visibility. Wheeler (1974) has documented the importance of marine fog to naval operations historically and has submitted representative statistics of losses in dollars and lives suffered by the United States Navy as a direct consequence of low visibility due to marine fog.

Realizing the importance of marine fog to maritime shipping, various Department of Defense (DOD) activities have engaged in research involving the analysis, modeling, and forecasting of fog over open oceans. Englebretson (1974) lists the participating DOD activities and outlines their respective research goals. The Naval Postgraduate School (NPS) group, in particular, is primarily focusing on the

analysis and forecasting of marine fog. A portion of the group has addressed the problem of marine fog climatology and developed a method of synthesizing ships' surface synoptic reports for the purpose of assessing the climatological frequencies of marine fog (Renard, Englebretson, and Daughenbaugh, 1975). The scheme continues under development.

Climatology is generally dependent on large volumes of data, hopefully near-uniformly distributed both spatially and temporally. However, a climatology of any given parameter over regions where the data coverage ranges from sparse to relatively abundant has certain obvious biases that may render misleading results. For example, for a geographical area outside of the normal shipping lanes where few or no ships pass, a general fog climatology might show the area "fog-free." In reality, the climatologist is probably not saying there are no occurrences of fog in that area, but merely that there are no "reported" occurrences of fog in that region. Other problems innate to climatologies compiled from conventional synoptic ship data are described by Renard, Englebretson, and Daughenbaugh (1975). However, it should be pointed out that climatologies thus derived are probably the best achievable for the current "state of the art."

What the meteorologist really desires then is some sort of data-taking apparatus that would give better temporal and spatial continuity to an <u>observable</u> phenomenon. Such an instrument might be the meteorological satellite <u>provided</u> the phenomenon being observed is, in fact, remotely discernible

by satellite sensors. Several satellite meteorologists in the field have suggested the satellite approach for detecting marine fog while, for example, Anderson, et al (1969), who treat the subject of weather-satellite applications in depth, do not even address the subject of open-ocean marine fog. If it can be determined that marine fog is discernible by satellite sensors, complete real-time description of fog distribution may at last be a reality. Hence, the time has come in the marine fog studies to determine whether or not marine fog is observable by current sensors on board meteorological satellites.

## B. OBJECTIVE AND APPROACHES

The objective of this study was to determine the feasibility of using meteorological satellite data, visual and/or infrared in any format, as means of discerning marine fog, its intensity, and its spatial extent. There were basically two approaches taken to achieve this objective. The first was a qualitative and semi-quantitative interpretation of satellite imagery in order to derive and set forth qualitative guidelines by which trained meteorologists at field activities could establish the existence and extent of marine fog from visual and/or infrared satellite imagery with some degree of positive skill. The second was the processing and quantitative interpretation of digital satellite data in order to establish the importance of applying numerical

techniques to satellite-derived data as a means of more accurately and objectively outlining regions where marine fog exists.

## C. DATA

### 1. Synoptic Ship Data

Transient-ship synoptic-time weather observations, used basically as "ground truth" for the existence or non-existence of marine fog, were obtained from two sources. The first source was the National Climatic Center (NCC), Asheville, North Carolina; the data were provided by the Naval Weather Service Detachment (NWSD), Asheville, North Carolina, on magnetic tape in a format known as Tape Data Family-11 (TDF-11), Surface Marine Observations. The second source was the Fleet Numerical Weather Central (FNWC), Monterey, California; these archived observations were also provided on magnetic tape in a format referred to as SPOT.

TDF-11 was provided for summer (June through September) 1973. Since the data were so nearly current at the time of request, the usual NCC quality checks had not been made. This absence of quality control probably rendered the data more representative of "unpurged," real-time synoptic observations. Computer software was written to extract pertinent information from the 140 character TDF-11 format and reformat it in standard ship synoptic weather code.

SPOT was pre-processed at FNWC to provide a printed copy of synoptic ship observations in an abbreviated, easily

readable format. These synoptic data were randomly checked against the TDF-11 to ensure that one source was not collecting more or different data than the other. It was found that, generally, for (militarily) unclassified data the two sets were nearly identical. The eventual purpose of this comparison was to determine the aptness of synoptic charts plotted from the FNWC SPOT using the FNWC CDC 6500 digital computer and on-line Varian electrostatic plotter.

2. Sea-Level Pressure Analyses

National Meteorological Center (NMC) Northern Hemispheric sea-level pressure analyses on microfilm were provided by the Environmental Prediction Research Facility (EPRF), Monterey, California. The NMC analyses were used for determining general synoptic weather patterns, particularly major cyclones, frontal activity, and surface wind flow. In addition, the plotted synoptic ship observations were employed as a tertiary source of raw synoptic data.

3. Meteorological Satellite Data

a. NOAA-2 (ITOS-D) Satellite Data

NOAA-2 data were obtained from two sources. EPRF provided 8"x10" photographic enlargements of hemispheric digitally composited mosaics for the scanning radiometer daytime visual (SRVIS), daytime infrared (SRIR-DAY), and nighttime infrared (SRIR-NGT) observations. Composited digital SRVIS and SRIR data on magnetic tape were provided by the NCC through the NWSD, Asheville, North Carolina. Both the mosaics and the digital data were originally processed by

the National Environmental Satellite Service (NESS), Washington, D. C. NOAA-2 data were selected for this study primarily because of the worldwide availability of NOAA satellite readout (direct or archived) information to civilian and military activities.

The NOAA-2 satellite is in a near-circular early morning/early evening orbit at an average distance of 783 nmi (1451 km) from the earth. Equatorial satellite sub-point crossing times occur near 2100 local northbound and near 0900 local southbound. The orbital period is 115 minutes or roughly two hours.

The NOAA-2 scanning radiometer has a visual channel with a spectral response of 0.5um to 0.7um and an infrared window channel with a spectral response of 10.5um to 12.5um. The SRVIS channel has a 2 nmi resolution at the nadir point and the bandwidth of the spectral response is entirely continuous within the visual spectra. The SRIR channel has a 4 nmi resolution at the nadir point and is a relatively "clean" atmospheric window, oriented to the long wavelength side of the 9.6um ozone absorption band and to the short wavelength side of the 15um carbon dioxide absorption band (Cogan and Willand, 1974). Some absorption by water vapor does occur toward the long wavelength end of the IR spectral interval. (See Figure 1.) The usefulness of this water vapor sensitivity, especially in NOAA series Very High Resolution Radiometer (VHRR) IR data, for the

detection of lower tropospheric moisture and areas of possible fog formation, has been postulated (National Weather Service, Western Region Headquarters, 1974). It should be noted, however, that, although the absorption due to water vapor in the higher wavelengths of the NOAA IR band is substantial, it is still considerably less than the absorption for the atmosphere as a whole. (See Figure 1.)

The daily NOAA-2 mosaics used in this study were originally prepared by high speed digital computers. SRVIS and SRIR data obtained during the daylight portion of the orbit (i.e., southbound) are used in the 0900L mosaics; SRIR data obtained during the nighttime portion (i.e., northbound) are used in the 2100L mosaics. The scan-line analog signals from the satellite are digitized using analog-to-digital conversion equipment. The digital information is then processed, earth located, and overlaid on a standard polar stereographic projection. Where data overlaps on consecutive orbits, the more current data are used. A more complete description of the content and preparation of the mosaics is contained in any volume of Key to Meteorological Records Documentation (KMRD) No. 5.4 (NESS, 19XX).

The digital NOAA-2 data were provided on magnetic tapes. Each tape contained either the SRVIS and SRIR-DAY or SRIR-NGT for one date. The SRVIS/SRIR-DAY data were configured in a 2048 x 2048 mapped array for the Northern Hemisphere; documentation for each tape was contained in the first record of the data file; and records 2 through 2049

contained one line each of the 2048 count values, ranging from 0 to 255 (0 to 377 octal). The SRIR-NGT data were provided for the Northern and Southern Hemispheres; the first file contained the documentation record; the second file contained 2048 records of the 2048 x 2048 Northern Hemisphere SRIR-NGT count data; and the third file contained 2048 records of Southern Hemisphere data. A schematic of the tape layout for both sets of tapes is provided in Figure 2. For SRVIS, low order values indicate dark and high order values (254 maximum) indicate bright; for SRIR, low order values indicate cold and high order values (254 maximum) indicate warm. Value 255 ($377_8$) is reserved for denoting "void" areas which appear either as the peripheral background or as data-void regions. At NESS, current digital processing capabilities include such things as: corrections for atmospheric absorption (limb-darkening), conversion of IR radiances to equivalent blackbody temperatures, rectification to different map scales, and gray shade enhancement for IR imagery. A more detailed discussion of these and other processing techniques at NESS are discussed by Anderson, et al (1969).

EPRF has developed equipment and support computer software for a similar type processing of NOAA series data at Naval Weather Service Fleet Weather Centrals which possess CDC 3X00 processing capabilities. The Direct Readout Data Converter (DRDC), as it is referred to, and the DRDC support software package are designed to digitize, process, and

display the NOAA series DRSR data. One particular processing routine, called "Slice," produces an output picture which contains only a few discrete gray shades, each related to a specific temperature range (IR only) or brightness range (visual only). It has been speculated that this processing routine could be useful in marine fog studies. A complete documentation of the DRDC and DRDC software is provided by Hunolt (1974).

b. DMSP (formerly DAPP) Satellite Data

Satellite data from the Defense Meteorological Satellite Program (DMSP), formerly referred to as Data Acquisition and Processing Program (DAPP), were chosen for study because of the planned widespread availability of DMSP satellite direct-readout at Department of Defense weather activities both ashore and afloat. In addition, DMSP communications and ground processing systems are configured so that a usable product is available within five minutes of the termination of the transmitted data stream (Meyer, 1973).

DMSP satellites operate from an altitude of 450 nautical miles in sun synchronous orbits. Two satellites are normally maintained in orbit, one in the noon-midnight orbit and the other in the early morning-early evening orbit; the DMSP sensors are designed to function at any local sun time. The satellites cross the equator northbound at approximately 0830L/1230L and southbound at 2030L/0030L. The DMSP satellite visual sensors have a spectral response in the region between 0.4um to 1.1um which covers the

near-ultraviolet to near-infrared portion of the solar spectrum; this region was selected to optimize the distinction among clouds, ground, and water (Meyer, 1973). One of the two visual sensors has a 2 nmi resolution (H-format) for global coverage and the other sensor has 1/3 nmi resolution (V-format) for limited area coverage. In the preliminary studies for this project, the unique DMSP visual imagery showed promise as a tool for detecting lower tropospheric moisture, and/or aerosols and condensation nuclei; this aspect is discussed in more detail under "Procedures."

The infrared sensors cover the broad bandwidth of 8.0um to 13.0um which spans the so-called "atmospheric window." However, it is essentially a "dirty" window, being "contaminated" by water vapor, ozone, carbon dioxide and aerosols (Cogan, Tripp, and Isaacs, 1974). (See Figure 1.) The usefulness of such a broadband IR spectral response, especially as "dirty windows" for lower tropospheric moisture detection, has been proposed (Cogan and Willand, 1974; NWS, Western Region Headquarters, 1974). Like the visual sensors, one IR sensor has a 2 nmi resolution (I-format) for global coverage and another IR sensor has 1/3 nmi resolution (W-format) for regional coverage.

Unlike the NOAA series satellites which transmit sensed information as an analog signal, the DMSP satellite data are digitized onboard and transmitted in digital format rendering the data digitally processable upon receipt. For example, the IR output voltages are converted onboard the

satellite to a linear function of the equivalent blackbody temperature of the scene (to give a uniform temperature resolution) within a temperature range of 210-310K and then transmitted to earth for direct processing (Blankenship and Savage, 1974). In addition to the ability to process IR data at various temperature ranges and thermal resolutions, the current DMSP processing and display equipment has the capability of so-called "threshold processing" whereby switch selectable threshold values may be established at three IR temperatures within the 210-310K range. The output image contains four shades of gray corresponding to temperature intervals within the chosen interval. (This is very similar to EPRF's "Slice" technique described on page 18.) It has been speculated that this threshold processing might be extremely helpful in lower tropospheric moisture and fog studies. Blankenship and Savage (1974) and Meyer (1973) give a rather brief but concise overview of the DMSP sensors and electro-optical processing capabilities.

DMSP data for the North American and the North Pacific Ocean areas for June through September 1973 were obtained from the Air Force Global Weather Central, Offutt Air Force Base, Omaha, Nebraska, before they were systemically degaussed. Also obtained were the accompanying ungridded image transparencies of the H- and I-configured data. The AFGWC converted the raw encrypted H and I DMSP satellite data to mapped data format (enhanced and rectified) with accompanying photographic imagery of the gridded

spin-scan display on a 1:15 million polar stereographic projection. The conversion of the raw encrypted data to mapped data format renders the data computer processable and earth locatable.

c. NIMBUS-5 Temperature-Humidity Infrared Radiometer (THIR) Data

NIMBUS-5 THIR gridded film strip imagery for the 6.7um (6.5-7.0um) and 11.5um (10.5-12.5um) channels were obtained for EPRF. The 6.7um water vapor channel gives information on the moisture content of the upper troposphere and stratosphere and thereby jet stream and frontal activity (Goddard Space Flight Center, 1972). For this reason, the 6.7um channel imagery was only briefly perused and then disregarded for this study. The THIR 11.5um window channel provided day and night cloud top or surface temperatures (for clear column radiances). The 11.5um channel has essentially the same spectral response as the NOAA-2 SRIR sensor, i.e., 10.5um to 12.5um. According to Cogan et al (1974), the NOAA-2 SR sensor is "better" than that of the NIMBUS-5 THIR 11.5um channel in terms of less atmospheric attenuation. Even though atmospheric attenuation, especially water vapor absorption, might be beneficial in fog detection studies, the difficulty in viewing the gridded film strip imagery precluded its use in this study for other than as a verifying aid in questionable areas. Moreover, the NIMBUS series satellites are not designed for direct readout capabilities and thus cannot be used for real-time meteorological operations.

Figure 1 has been provided for a comparison among the spectral bands covered by the NOAA-2, DMSP satellites, and NIMBUS-5 THIR 11.5um sensors relative to the atmospheric absorption spectra. Figures 3 and 4 are samples of the THIR 11.5um channel, NOAA-2 SRVIS and SRIR-DAY, and DMSP V, H, and I imageries.

# II. PROCEDURES

## A. SELECTING THE GEOGRAPHICAL REGION AND TIME PERIOD

The geographical area for this study was chosen to be the North Pacific Ocean from 30N to 60N latitude between 115W and 180 longitude. (See Figure 5.) This region was selected to nearly coincide with part of the area that Renard, Englebretson and Daughenbaugh (1975) used in developing climatological marine fog frequencies. This North Pacific Ocean area afforded a suitable domain in which both maxima and minima of fog frequencies occur, as shown in Figure 6. Choosing the area of study in this manner insured that the "field-of-view" would be large enough to include the critical boundaries between fog and no-fog.

The time period of this study was selected based on a pre-screening of National Meteorological Center (NMC) six-hourly synoptic surface charts (i.e., 0000 GMT, 0600 GMT, 1200 GMT, 1800 GMT) for the months of June through September 1973. Periods when fog existed over a significant portion of the study area, as revealed by the transient-ship reports and/or synoptic features, were then noted. These selected periods were compared to the dates and times for which data existed simultaneously from DMSP, NOAA-2, and NIMBUS-5 satellites. With regard to the longest continuous period for which data existed from all satellite sources, the limited

period of 17 July through 6 August 1973 was selected for study.

The 1:15 million polar stereographic projection was chosen as most practical for displaying the NMC sea-level pressure analyses, the NOAA-2 mosaics, and the DMSP imagery.

## B. PROCESSING TRANSIENT-SHIP SYNOPTIC-TIME DATA

### 1. Sorting and Categorizing TDF-11 Data

Once the TDF-11 data had been reconstructed into the convenient standard synoptic format for ships, only reports within the time-frame of the study were retained and printed. Additionally, for easier use, the ship reports were sorted by primary synoptic reporting times, i.e., 0000 GMT, 0600 GMT, 1200 GMT, and 1800 GMT. Data for other time periods were preserved separately in order to provide temporal continuity. The total number of reports for the primary reporting times totaled 5053.

Computer software was then written to scan the ship reports within the primary synoptic periods for fog or fog-related parameters, categorize them according to Table I, and print them in the format displayed in Figure 7. This codification was performed to provide overall fog statistics for the study period and also to aid in selecting a shorter time period within the 21-day primary period for a more in-depth study. The sorting of the fog reports revealed that present-weather fog reports comprised 20.25% of the 5053 reporting ships. More generally, the categorization of the

fog reports revealed some remarkable internal inconsistencies within the synoptic reports which reflected upon the capability of establishing the existence of cloud layers above reported fog and hence any higher cloud "contamination" that might be expected in satellite data. For example, a common problem occurs in the reporting of total cloud amount (N) consistent with the fog-type which is reported. In numerous cases, code figure 8 (i.e., 10/10 cloud cover), vice 9 (i.e., sky obscured), is reported for "N" while code figure 43, 45, 47, or 49 (fog, sky <u>not</u> discernible) for "ww" is simultaneously reported. Also, there are cases where code figure 9 is reported for "N" and clouds at one or more levels are reported (i.e., for $C_l$, $C_m$, $C_h$). In any event, 75% of all ships reporting fog also reported an obscuration of the sky or a type of fog that implied that the sky was obscured. The task of establishing some "ground truth" of higher level clouds (types and amounts) with the existence of fog at sea (i.e., stratus within 33 feet of the surface of the water) is virtually impossible. Thus, the hope of establishing cloud types *a priori* from transient-ship weather reports for satellite observations was abandoned as a routine procedure in this study. However, this did not prove to be restrictive except when fog existed and was reported within frontal bands where multilevel-clouds exist.

2. <u>Plotting Synoptic Data from SPOT</u>

Computer software was written for the FNWC CDC 6500 to plot the ships' weather data for the 84 six-hourly,

synoptic charts covering the 21-day study period. The software was designed to extract SPOT data from a FNWC climatology tape and display the data on the appropriately generated 1:15 million polar stereographic background. The data were color-coded to depict present-weather fog, past-weather fog, or cloud-types (for ships not reporting fog) and specific areas of fog and no-fog were subjectively generalized from the synoptic reports.

## C. PREPARING SEA-LEVEL PRESSURE ANALYSES

The NMC sea-level pressure analyses were provided on microfilm. In order to more readily use the charts, the microfilmed analyses were photographically enlarged to 1:15 million. By thus enlarging the analyses, plotted synoptic data and/or satellite imagery could be easily compared to various features and parameters in the analyses. The fog/no-fog areas were subjectively adjusted, as necessary, to synoptic features particularly near fronts, along the periphery of anticyclones, and in areas under southerly flow across the cold waters near the Aleutian (subarctic) ocean current.

## D. PROCESSING NOAA-2 MOSAICS AND THE USE OF NOAA-2 IMAGERY FOR DISCERNING MARINE FOG

In order to view the NOAA-2 mosaics on the same scale as the plotted transient-ship weather data and sea-level pressure analyses, it was decided to photographically enlarge each of the SRVIS, SRIR-DAY, and SRIR-NGT mosaics to 1:15 million

for the study area. There are approximately 99 digital scan lines per centimeter advancing from the top to the bottom of the normal 20.7 x 20.7 cm mosaic. Since the enlargement process required a 7.8 expansion of the mosaic, the enlarged imagery has roughly 13 scan lines per centimeter. As a result, the photographically enlarged imagery showed some degradation in the sharpness of the gray shades. There were a few cases where this degradation was aggrevated apparently by other processing problems including the initial mosaic reproduction. The result was that some of the reproductions were generally too dark within the study area. This factor was influential in the subsequent choice of the narrower time period for a detailed study.

In the area of concern, i.e., 30N to 60N between 115W and 180, there are primarily four NOAA-2 passes which are eventually digitized and combined to create the day composites (SRVIS and SRIR-DAY, satellite southbound) with approximate ascending nodal times of 1648 GMT, 1848 GMT, 2048 GMT, and 2248 GMT (stepping east to west on successive orbits). This means that the time when the satellite has a subpoint of 60N is roughly 40 minutes after ascending node (AAN) or 1728 GMT, 1928 GMT, 2128 GMT, and 2328 GMT. The satellite then crosses 30N approximately ten minutes later. Since the westernmost pass (AN 2248 GMT) is used only in the extreme northwest portion of the area of study, the primary synoptic data used for the day mosaics were for 1800 GMT with the 0000 GMT data being used secondarily for

continuity. Similarly for the night composites (SRIR-NGT, satellite northbound), the times of ascending node were 0448 GMT, 0648 GMT, 0848 GMT, and 1048 GMT. The satellite subpoint crosses 30N ten minutes later and crosses 60N at approximately 0508 GMT, 0708 GMT, 0908 GMT and 1108 GMT (stepping east to west on successive orbits). Thus the 0600 GMT and 1200 GMT synoptic data were the primary and secondary verifying "ground truth", respectively, for the night composites.

A comparison was then made between the verifying synoptic data and the satellite imagery. Gray shade variations in the satellite imagery were noted in areas where fog was reported particularly along the discernible boundaries of varying gray shades which coincided with fog/no-fog boundaries inferred from the verifying synoptic data. Each of the twenty-one simultaneous SRVIS and SRIR-DAY and the twenty-one SRIR-NGT enlarged mosaics were compared to the verifying ship data and significant features were documented. At the same time, a subjective assessment was made as to the overall quality of each enlarged mosaic and to the quantity of verifying data; this information was used as an additional aid in selecting a sub-study period from the 21-day period.

Generally, it was found that, for areas unobscured by middle and high level clouds, it was possible to pick out areas of low level clouds and further distinguish stratus and/or fog from cumulus type clouds. There was no apparent gray shade variation detectable between areas reporting fog

and those reporting code figure 6 for "$C_1$" (i.e., stratus in a more or less continuous layer and/or ragged shreds, or both, but no stratus fractus of bad weather). However, there were discernible differences between areas of reported fog and other types of stratiform clouds where some vertical motion is implied, e.g., stratocumuliform clouds (code figure 4, 5, or 8 for "$C_1$"). Moreover, when using simultaneous SRVIS and SRIR-DAY imagery together, subtle variations in both visual and IR frequently did occur in the vicinity of fog/no-fog boundaries. In good imagery, i.e., with good gray shade variation and relatively undistorted through photographic enlargement, the boundaries were more obvious. This led to the belief that the EPRF DRDC "Slice," DMSP threshold processing, or any similar digital processing would be extremely useful in discerning marine fog.

After looking at the twenty-one days of satellite imagery and documenting the results, skill was developed in correlating gray shade variations with verifying fog. As a result a set of seven qualitative guidelines were formulated for discerning areas where the satellite imagery indicated that fog was occurring. The guidelines are offered as Appendix A.

The next step was to re-screen the satellite imagery and the documentation compiled during the first screening in order to select a sub-study period. Considering as many factors as possible, the period selected was 241800 GMT through 270000 GMT July 1973. This period included a set of

three SRVIS/SRIR-DAY mosaics and two SRIR-NGT mosaics. The first six qualitative guidelines were then applied as objectively as possible to the eight enlarged mosaics and areas of "fog," "no-fog," and "frontal clouds" (i.e., multilevel clouds) were established for the five primary synoptic study times, i.e., 241800 GMT, 250600 GMT, 251800 GMT, 260600 GMT, and 261800 GMT. The secondary times (250000 GMT, 251200 GMT, 260000 GMT, 261200 GMT, and 270000 GMT) were used wherever necessary for continuity. The areas diagnosed as "fog" were then verified against the synoptic reports and the statistics were compiled as shown in Table II. For the five study periods, the results showed that roughly 70% of the fog reports fell into the areas deemed, from the satellite imagery, to be fog areas. The skill of discerning fog as compared to chance (Panofsky and Brier, 1968) was positive for all cases except for the SRIR-NGT for the first night period, 250600 GMT, which was -0.06. The skill scores for each time period for the cases of including and excluding the "frontal" data are also shown in Table II.

Generally, the results show that one can discern areas where fog exists with some degree of positive skill based on the guidelines offered. In addition, it is believed that with better imagery the score could have been even higher. Hence, these results led to the use of the digital NOAA-2 data, from which the mosaics were derived, for more objectively discerning marine fog and its horizontal extent.

## E. PROCESSING NOAA-2 DIGITAL COUNT DATA AND THE USE OF DIGITAL INFORMATION FOR DISCERNING MARINE FOG

The NOAA-2 digital count data were provided on magnetic tape and configured as shown in Figure 2. The digital count data were obtained only for the sub-study period. The data values, ranging from 0 to 255, were for a 2048 x 2048 grid-point array which coincided with the 20.7 x 20.7 cm digitally composited mosaics. A schematic of the mosaic background is provided in Figure 5 with the area of study within the shaded portion. The rectangular box incorporating the oceanic part of this area represents the outside boundaries of the data subpoints extracted from the 2048 x 2048 array for detailed processing. The rectangular region is oriented, for convenience of processing, so that the rows and columns of the sub-grid area are parallel to the rows and columns of the larger grid. The actual rows and columns for the sub-grid area relative to the larger grid were determined by simple linear ratios involving 1) the linear distance from the edges of the larger grid to the smaller grid boundaries, 2) the total length of the larger grid (20.7 cm), and 3) the total number of grid spacings for the large grid (2047). For example, the uppermost grid row was found by taking the ratio (9.3 cm):(20.7 cm)::y:(2047 spacings) and solving for *y*; in this case, *y* equals 920 grid spacings. Thus it was determined that the rows ranged from 921 to 1500 and the columns from 446 to 792. This gave a 347 x 780 grid array for the sub-grid area.

The same geographical area covered by the sub-grid area was outlined on a 1:15 million polar stereographic chart and then measured to determine its size and the expansion factor of 7.8. The area, outlined on the 1:15M, measured 18 x 10 3/4 inches. This rectangular area was then divided into a 1/4 inch meshlength grid. In order to transform the array of values from the finer mesh (approximately 1/32 inch at 1:15M) to the 1/4 inch meshlength grid at 1:15M, it was necessary to extract roughly every eighth grid point. The 1/4 inch meshlength gives a resolution of approximately 51 nmi at 60N and 45 nmi at 30N. Computer software was written to print all count values within the sub-area and also to print every eighth value, corresponding to the 1/4 inch meshlength grid; the 1/4 inch meshlength values were printed at 1/4 inch intervals so that clear acetate could be overlaid and a hand analysis made of the values.

A rough hand analysis was then made of the 1/4 inch mesh digital count data for one SRVIS, SRIR-DAY, and SRIR-NGT mosaic to determine a realistic range of values for computer analyzing the data at finer meshlengths. A range of 60 to 200 digital counts for both SRVIS and SRIR was found to be realistic. Attempts were then made to analyze the count data for the full 1/32 inch and 1/16 inch meshlength grids at 20-count intervals between 60 and 200. However, the analysis software (NPS software-library routine "CONTUR") was not capable of processing at these meshlengths. The smallest successfully analyzable meshlength was 1/8 inch (approximately

24 nmi resolution). It was then found that the 20-count interval analyses were basically too "noisy" for practical usage.

Therefore, the next step was to correlate digital count values with verifying fog reports. The range of count values for two SRVIS, two SRIR-DAY, and two SRIR-NGT cases (241800 GMT through 260600 GMT July 1973) are shown in Table III. It was also found that, for the SRVIS, digital counts less than 60 corresponded to generally cloud-free conditions; Cogan and Willand (1974) found that values less than 80 corresponded to very few or no clouds.

Based on these values, the SRIR data were analyzed at values of 60, 120, 175, and 190 digital counts (roughly 224.0K, 263.0K, 291.0K, and 298.0K, respectively). The SRVIS data were analyzed at 60, 120, and 180 counts. Samples of the SRVIS, SRIR-DAY, and SRIR-NGT analyses are shown in Figures 8, 9, and 10. For the daytime data, ocean areas in which the SRIR-DAY count values were between 120 and 175 and which also were <u>not</u> cloud-free (i.e., the SRVIS count values were greater than 60) were diagnosed as fog areas. For the nighttime data, areas where the SRIR-NGT count values merely fell between 120 and 175 were diagnosed as fog areas. The verification scores using these "cut-off" digital count values are contained in Table IV. For all but one time period, a considerable improvement in skill scores occurred; the first SRIR-NGT case even showed a change of sign in the skill scores (i.e., "chance" was beaten). Even more noticeable is the fact that all verifying fog reports fell into an area diagnosed as either

"fog" or "frontal" (i.e., multilevel clouds). More specifically, 87% of the verifying fog reports fell into a fog-designated area. Additionally, it was found that areas of multilevel clouds ("frontal") were more precisely defined in the computer produced display than in the enlarged mosaic imagery.

Thus, it was concluded that, for this particular sample of data, it was possible to diagnose marine fog with a good degree of positive skill using properly processed NOAA-2 digital count data.

## F. PRE-PROCESSING DMSP SATELLITE IMAGERY

In the preliminary studies for this project, the DMSP satellite imagery in the form of transparencies, showed great promises as a tool for detecting lower tropospheric moisture and stratus and fog. The transparencies, for which the data were earth-locatable (usually along the west coast of North America), were compared to verifying transient-ship synoptic weather reports. Generally the I-format IR imagery showed similar results as the NOAA-2 SRIR except for resolution. The H-format visual imagery and, particularly, the V-format visual imagery showed some rather remarkable features which were not apparent in the NOAA-2 SRVIS. For example, along the periphery of reported stratus/fog bands, the white stratus/fog diminished to a very light shade of gray (lighter than the darker clear areas over the open ocean). This light shade of gray invariably extended around the entire

periphery of the stratus or fog and frequently extended downwind of the cloud mass for several hundred kilometers.

In this respect, it is to be noted that the upper portion of the DMSP visual spectral interval in Figure 1 overlaps the water vapor region of the atmospheric absorption spectra. In the "positive" visual imagery, one would expect darkening of the gray shades if attenuation due to water vapor absorption was dominating. However, the imagery actually showed a lightening of the gray shades where one would expect to have greater concentrations of lower tropospheric moisture. This led to the belief that the attenuation (if it is in fact attenuation) is due to scattering, diffraction, or reflection from condensation nuclei, aerosols, or small cloud droplets. According to Rayleigh Theory, the ideal ratio of the diameter of a spherical particle to the wavelength of incident radiation for scattering is 0.1. Thus for the DMSP visual spectral response of 0.4 to 1.1um, particles of size of 0.04 to 0.11um would cause Rayleigh scattering. This would include such particles as Aitken nuclei, haze, and small condensation nuclei. For two particular periods studied, there were verifying ship reports across the boundaries of the bright-white stratus/fog and the light-gray shaded area; in both cases ships beneath the brighter portion reported fog and ships beneath the light-gray areas reported haze.

Thus, it is suspected that the DMSP satellite visual imagery may be extremely helpful in locating fog boundaries. Unlike the NOAA-2 SRVIS digital data, it is quite possible that a "cut-off" processing value may be determined for the

DMSP digitally mapped visual data as a means of isolating the boundaries of fog and no-fog. Hence, the visual data may then be used for more than merely determining cloud-free regions to be used in conjunction with IR data.

As of the writing of this thesis, the DMSP satellite data, which was processed by AFGWC, had not been received; therefore, a thorough investigation into the DMSP satellite data for the entire area of study was not performed.

## III. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDIES

It was the objective of this study to determine the feasibility of using meteorological satellite data for discerning marine fog. It is believed that sufficient evidence is presented, from the small sample taken in this study, to justify further investigations into the real-time use of satellite data for diagnosing marine fog. Both the qualitative guidelines in Appendix I and the numerical processing techniques used in this study showed the capability of positive skill in diagnosing marine fog. Furthermore, it is believed that refinements to these techniques could assuredly improve the diagnostic skills.

Therefore the following recommendations are offered for future studies:

1) Develop computer software to earth-locate the digital count values for NOAA-2, given any latitude and longitude of verifying "ground truth" data; then, more accurately determine the appropriate digital count values (SRVIS and SRIR) corresponding to verifying fog reports. Accumulate a large data sample of these values for the entire 21-day study period and statistically derive the best cut-off values for analyzing the digital count data. Determine the latitudinal variation, if

any, of the count values corresponding to verifying fog. Apply these cut-off values to the digital data for the full 21-day period.

2) Develop similar digital processing software for the DMSP mapped digital data whenever it is received from AFGWC. Also, test the qualitative guidelines in Appendix A and amend them as deemed necessary.

3) Perform a real-time test of NOAA-series DRSR data by a live recording of the current NOAA satellite at NPS, converting the data using the DRDC at FNWC, and digitally processing the data using the DRDC support software at EPRF (in particular, utilize the "Slice" processing technique).

4) Perform a real-time test of DMSP satellite data by requesting threshold processing of direct-readout DMSP data received at the Naval Weather Service Facility, San Diego, California for the same periods as the NOAA series data described in 3) above.

If the numerical diagnosis of marine fog shows continued success, eventually a marine fog climatology of visual and IR digital count "cut-off" processing values can be compiled for every month of the year for various maritime regions of

the world using the same or similar techniques performed or recommended in this study. Whenever this stage in development is reached, a reasonable marine fog analysis may be a reality at last.

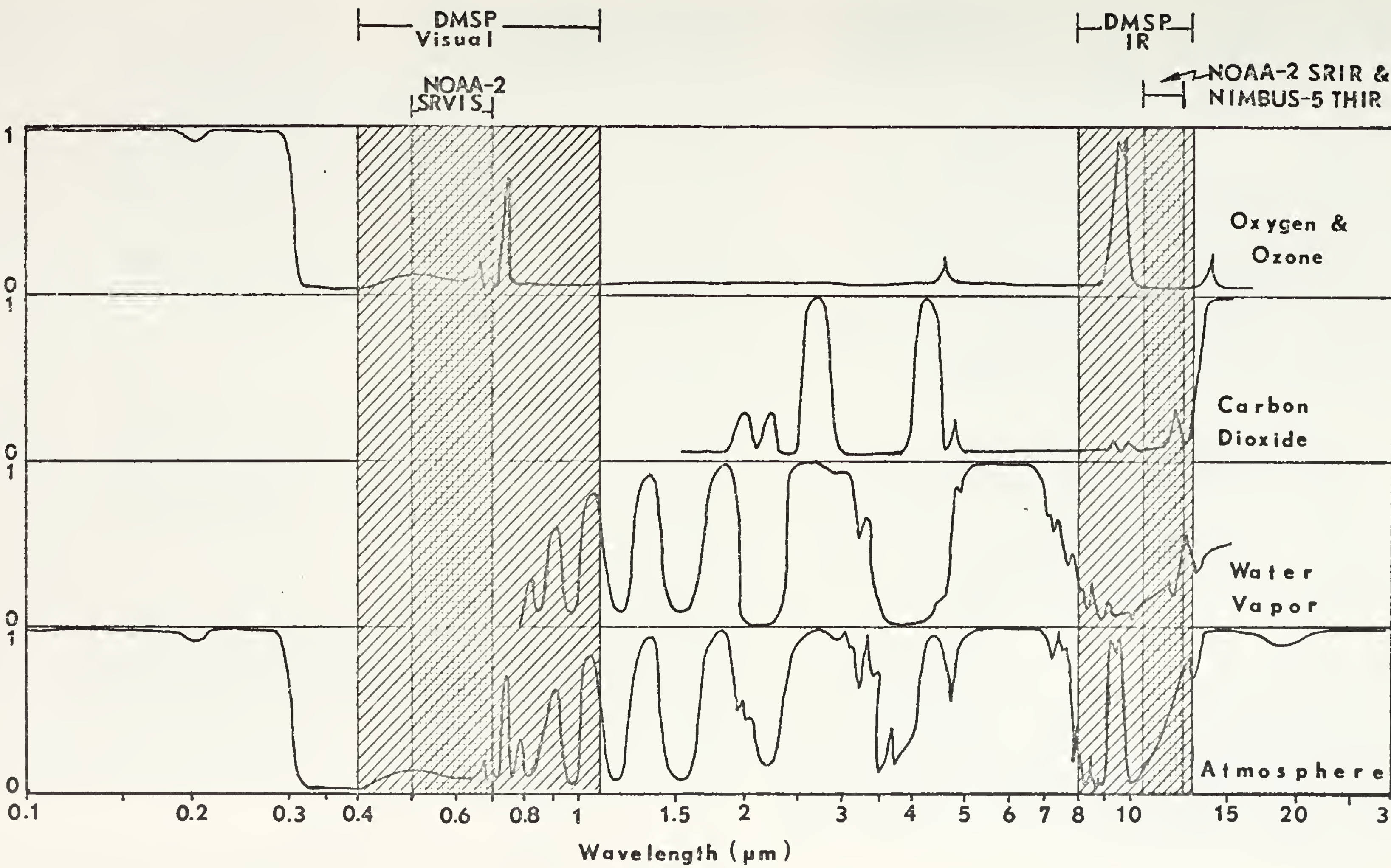
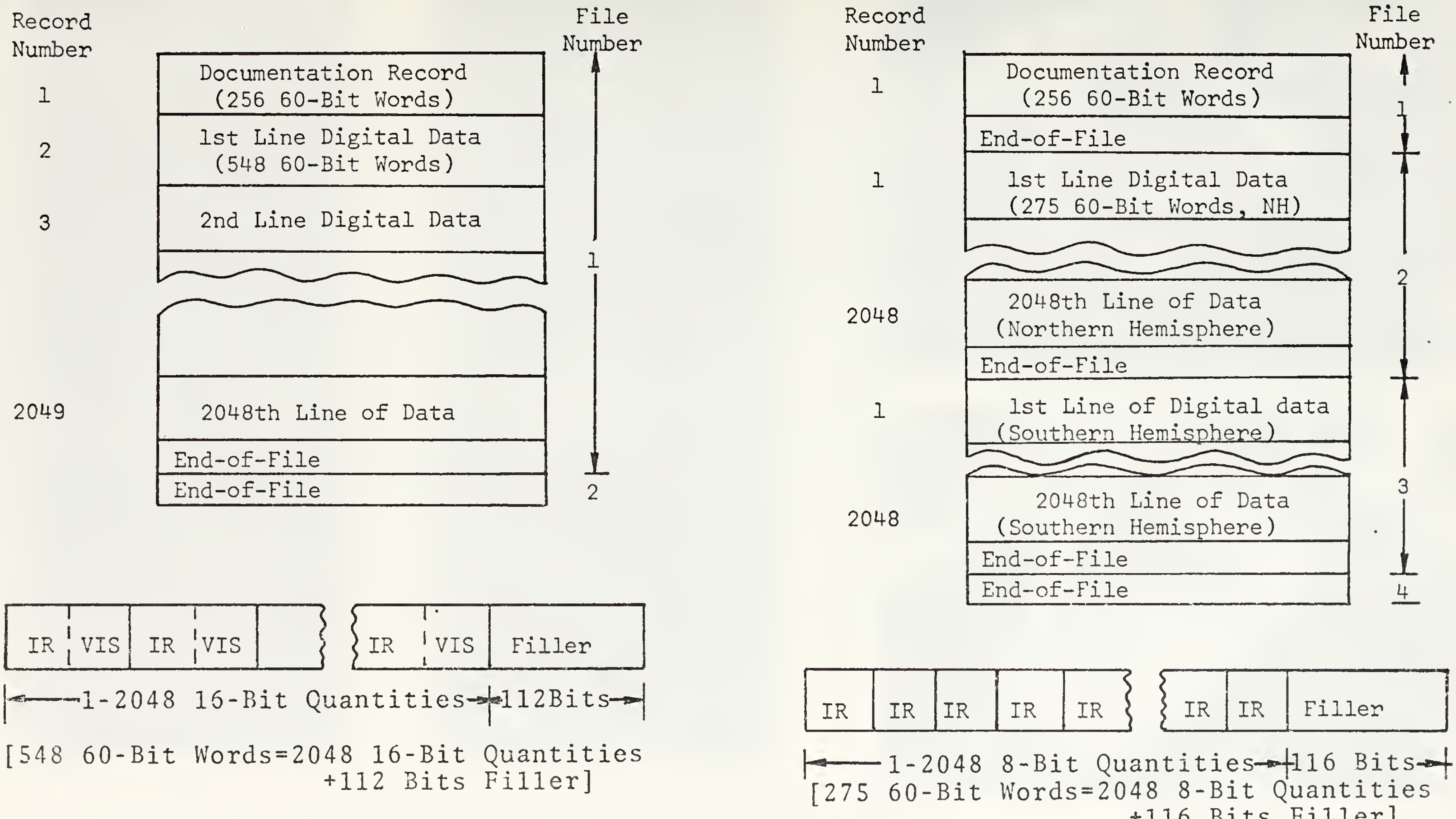


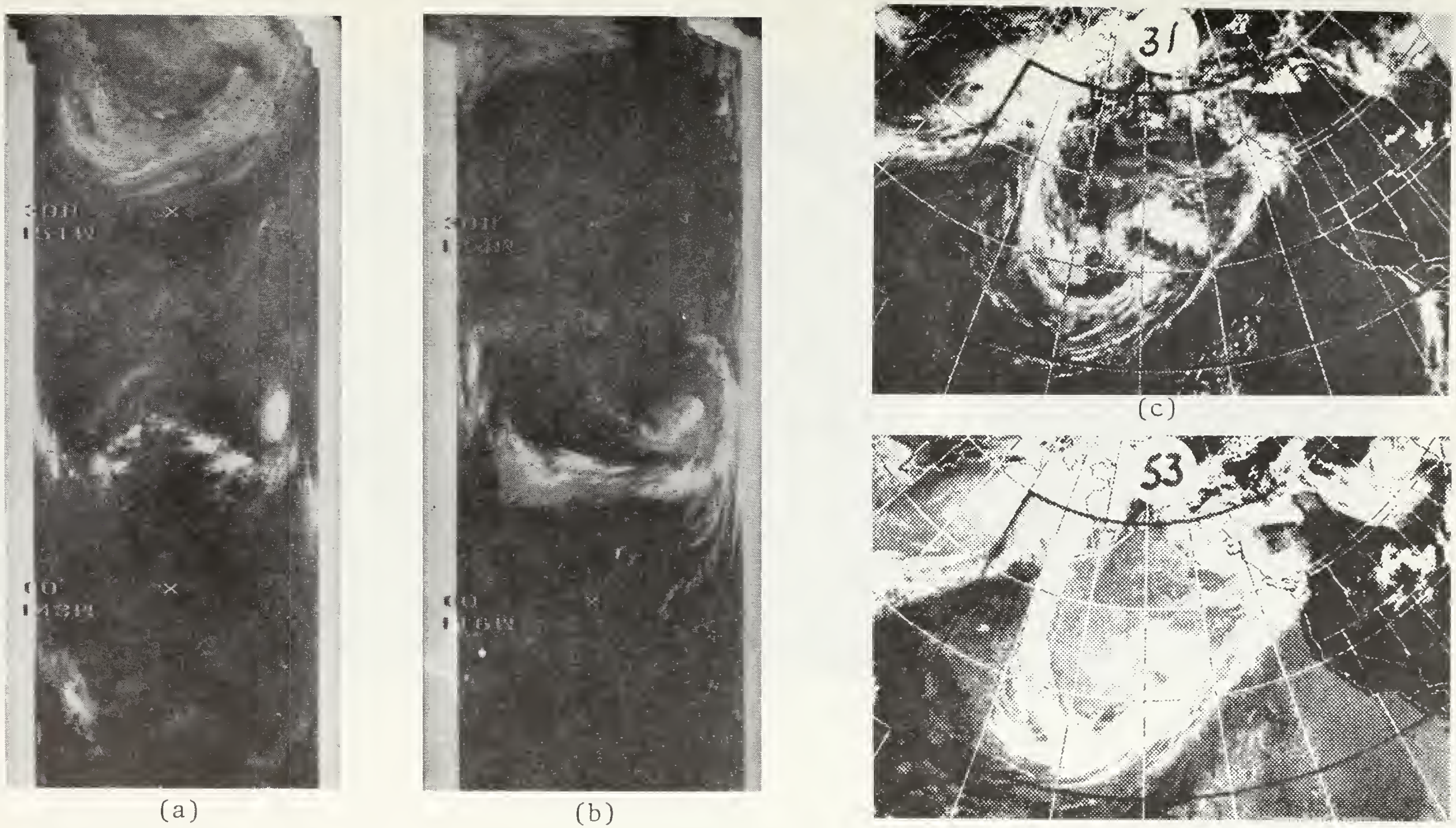

Figure 1. Absorption spectra for the atmosphere, water vapor, carbon dioxide, and oxygen and ozone.




(a) SRVIS and SRIR-DAY Tape Format

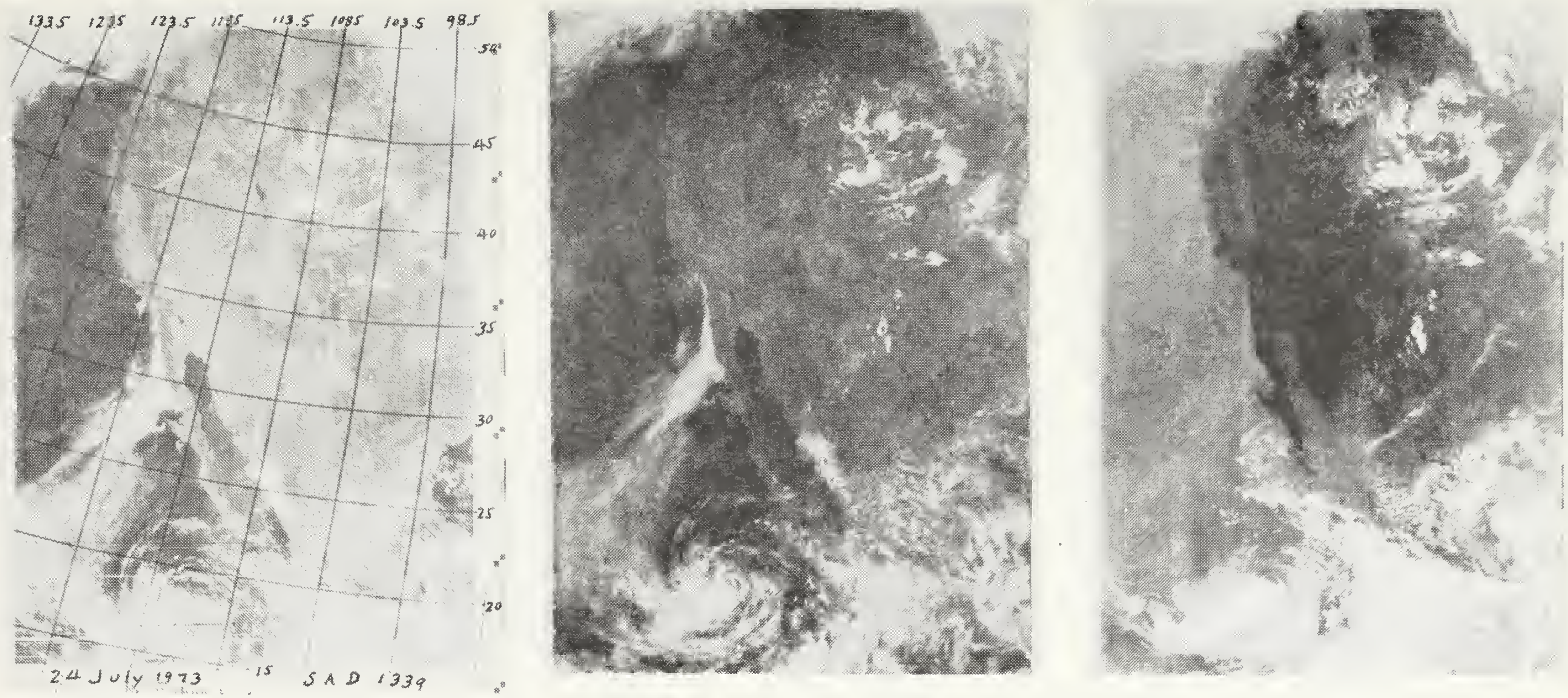
(b) SRIR-NGT Tape Format

Figure 2. Digital tape format for NOAA-2 SRVIS/SRIR-DAY and SRIR-NGT Data.




(a) (b) (c) (d)

Figure 3. Sample satellite imagery from NIMBUS-5 THIR 11.5um channel [day-northbound, 24 July 1973: (a) orbit 3028 and (b) orbit 3027] and for an extracted and enlarged portion of the NOAA-2 day-mosaics [southbound, 24 July 1973: (c) SRVIS and (d) SRIR-DAY].




(a) (b) (c)

Figure 4. Sample DMSP satellite imagery from satellite number 5528, orbit 6894 (near-noon northbound, 24 July 1973): (a) V-Format (1/3 nmi resolution visual); (b) H-Format (2 nmi resolution visual); (c) I-Format (2 nmi resolution infrared).

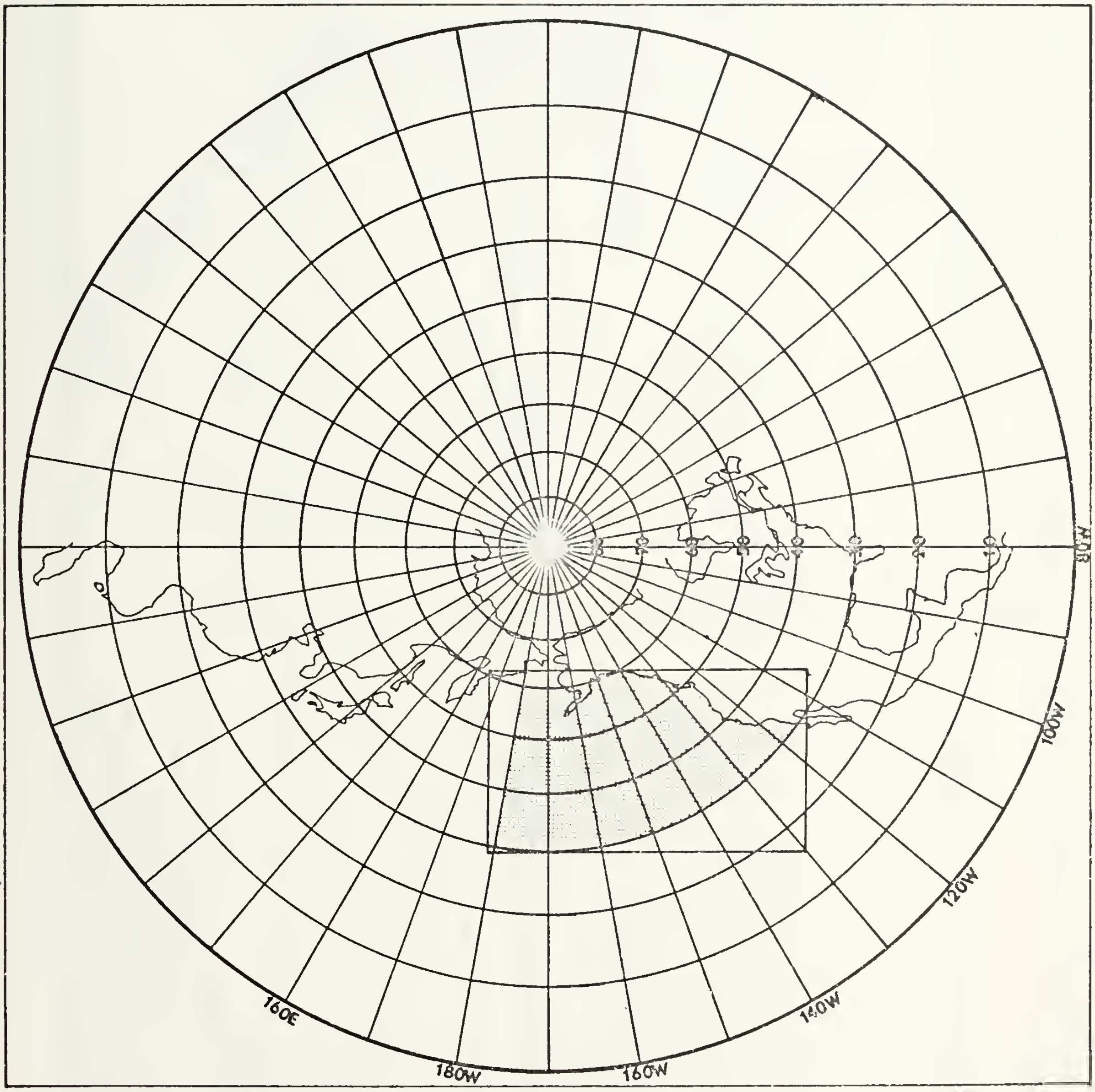



Figure 5. Background for digitally composited NOAA-2 mosaics with the North Pacific Ocean study area (shaded) and the rectangular area from which the digital SRVIS/SRIR data were extracted.

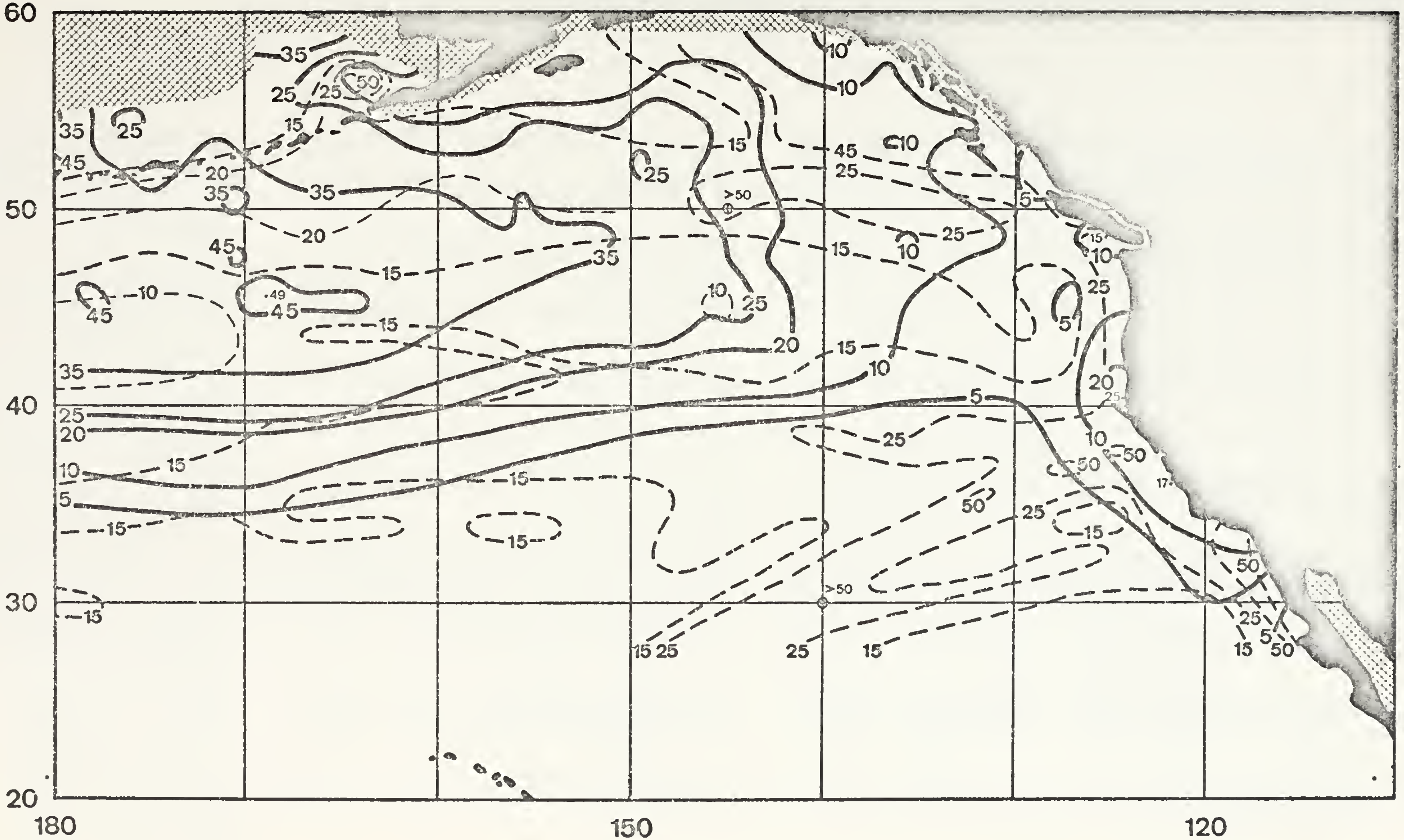



Figure 6. The July SSR marine fog frequencies (%) (solid lines) and number of days sampled in the period 1963-72 (%)(dashed lines)(Renard, Englebretson, and Daughenbaugh, 1975).

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| IRCS | CAT | LAT | LONG | WW | W | VV | N/NH | LO | MID | HI |
|---|---|---|---|---|---|---|---|---|---|---|
| WLRK | 1 | 50.5N | 131.3W | 10 | 1 | 97 | 8/8 | 6 | 0 | 0 |
| 5MRB | 4 | 53.5N | 150.9W | 47 | 4 | 92 | 8/8 | XX | XXX | XX |
| 3EZZ | 5 | 53.8N | 157.6W | 02 | 4 | 96 | 9/7 | 8 | 6 | 0 |
| EVRE | 4 | 44.0N | 124.5W | 40 | 0 | 94 | 9/9 | XX | XXX | XX |
| UIBC | 4 | 44.0N | 124.7W | 45 | 5 | 97 | 9/9 | XX | XXX | XX |
| UM?C | 1 | 44.6N | 124.7W | 10 | 4 | 97 | 8/8 | 6 | 0 | 0 |
| EWPK | 1 | 48.2N | 125.4W | 10 | 4 | 97 | 1/0 | XX | XXX | XX |
| WCGN | 5 | 48.1N | 135.8W | 01 | 4 | 98 | 8/8 | 5 | 0 | 0 |
| JGRB | 4 | 48.0N | 138.7W | 45 | 4 | 95 | 9/9 | XX | XXX | XX |
| GYZF | 4 | 48.5N | 143.3W | 45 | 4 | 94 | 9/9 | XX | XXX | XX |
| PESX | 5 | 49.9N | 144.7W | 61 | 4 | 96 | 9/9 | 0 | 0 | 0 |
| JXPL | 4 | 48.3N | 146.4W | 43 | 4 | 91 | 9/0 | XX | XXX | XX |
| UVPK | 3 | 41.5N | 163.5W | 28 | 4 | 99 | 2/2 | 6 | 7 | 4 |
| KHLX | 1 | 48.8N | 168.6W | 10 | 2 | 97 | 8/8 | 6 | 0 | 0 |
| ELQE | 5 | 42.4N | 169.3W | 38 | 4 | 97 | 9/0 | 0 | 0 | 0 |
| DGWL | 4 | 42.3N | 171.4W | 47 | 4 | 90 | 9/9 | XX | XXX | XX |
| JINJ | 4 | 48.5N | 171.9W | 45 | 4 | 93 | 9/9 | XX | XXX | XX |
| UTOL | 4 | 45.0N | 172.0W | 43 | 4 | 93 | 9/9 | XX | XXX | XX |
| 6ZOM | 1 | 40.2N | 172.6W | 10 | 4 | 95 | 9/9 | XX | XXX | XX |
| OVPU | 4 | 43.4N | 175.1W | 47 | 4 | 92 | 9/9 | XX | XXX | XX |
| OXMD | 3 | 40.0N | 177.2W | 28 | 4 | 97 | 8/8 | 0 | 1 | 0 |
| 6KCS | 4 | 44.1N | 178.5W | 45 | 4 | 90 | 9/0 | XX | XXX | XX |
| JXTX | 2 | 37.1N | 125.4W | 11 | 2 | 97 | 7/0 | XX | XXX | XX |
| JHCV | 3 | 38.1N | 160.0W | 28 | 5 | 96 | 8/8 | 8 | 2 | 0 |

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| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| GNUG | 2 | 52.2N | 158.1W | 11 | 2 | 98 | 6/6 | 6 | 0 | 0 |
| JGFM | 4 | 51.8N | 163.8W | 47 | 4 | 92 | 9/9 | XX | XXX | XX |
| SHIP | 1 | 45.0N | 124.6W | 10 | 2 | 97 | 9/9 | XX | XXX | XX |
| JGRB | 4 | 47.5N | 140.8W | 44 | 4 | 94 | 9/9 | XX | XXX | XX |
| PESX | 4 | 49.8N | 142.1W | 43 | 4 | 94 | 9/9 | XX | XXX | XX |
| JXPL | 4 | 48.4N | 143.6W | 45 | 4 | 94 | 9/0 | XX | XXX | XX |
| JMXT | 4 | 41.9N | 157.2W | 45 | 4 | 92 | 9/0 | XX | XXX | XX |
| JRAL | 4 | 40.0N | 157.7W | 47 | 4 | 92 | 8/0 | XX | XXX | XX |
| 601E | 4 | 43.0N | 161.7W | 42 | 4 | 97 | 9/0 | XX | XXX | XX |
| JRSM | 5 | 41.5N | 164.2W | 51 | 4 | 94 | 9/9 | 0 | 0 | 0 |
| WGXY | 4 | 44.1N | 164.9W | 47 | 4 | 91 | 9/9 | XX | XXX | XX |
| UTOL | 4 | 44.9N | 169.4W | 43 | 4 | 93 | 9/9 | XX | XXX | XX |
| JINJ | 4 | 47.3N | 173.3W | 41 | 5 | 94 | 8/8 | 7 | 0 | 0 |
| DGWL | 5 | 42.3N | 173.7W | 25 | 4 | 91 | 9/9 | 0 | 0 | 0 |
| JHAQ | 4 | 40.0N | 177.6W | 43 | 5 | 95 | 9/0 | XX | XXX | XX |
| NVKM | 1 | 45.4N | 177.7W | 10 | 5 | 97 | 8/8 | 6 | 0 | 0 |
| UNXE | 5 | 38.9N | 159.2W | 02 | 4 | 98 | 8/8 | 5 | 0 | 0 |

Figure 7. Sample output of sorted, reconfigured, and categorized transient-ship synoptic-time reports containing fog-related parameters. Output includes the International Radio Call Sign (IRCS) of the ship, the fog category (CAT), the latitude (LAT) and longitude (LONG) of the ship's position, the present weather code (WW), past weather code (W), visibility code (VV), total cloud amount/low-mid cloud amount (N/NH), and cloud types (LO, MID, HI) (X's indicate that the sky is obscured).

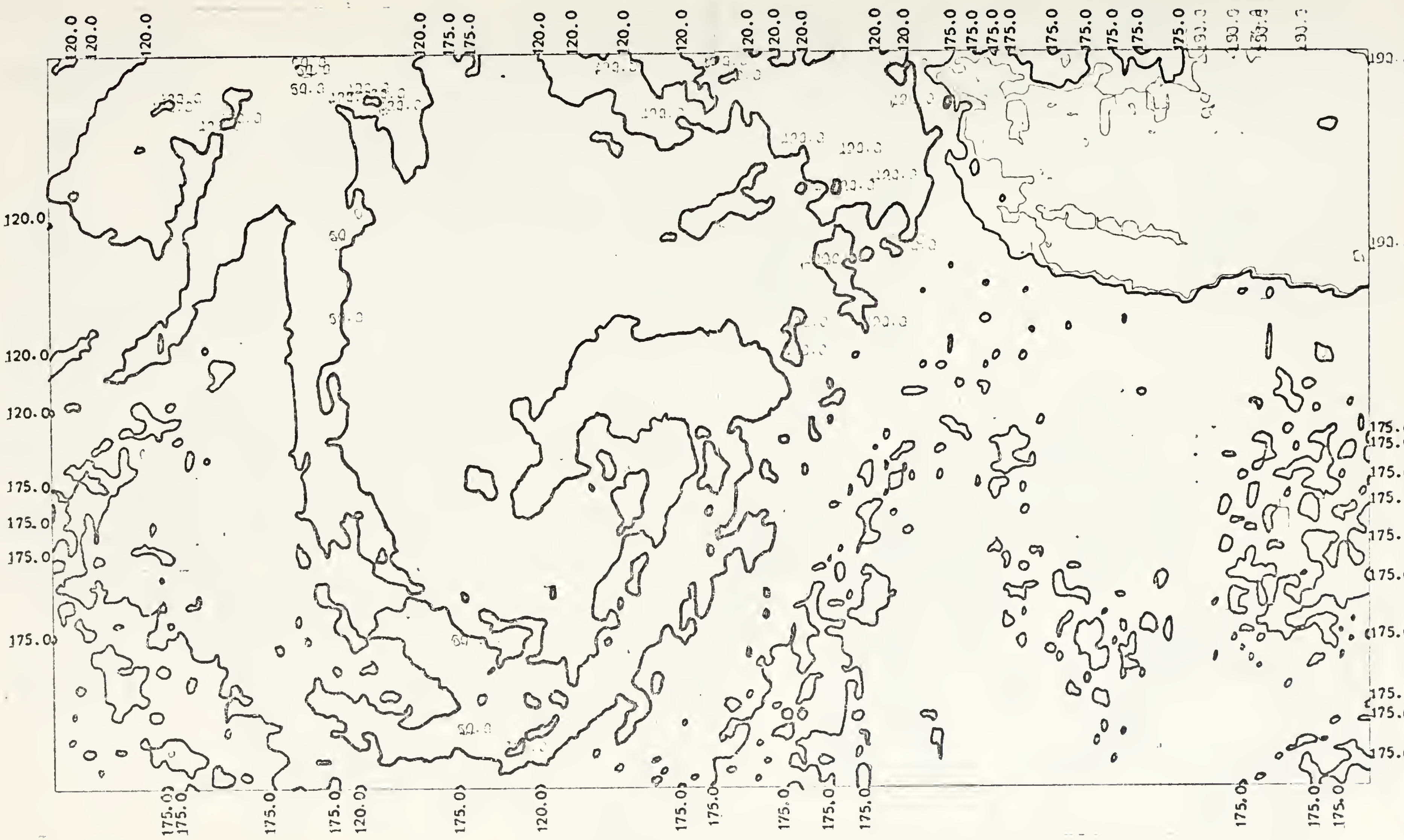

Figure 8. Analysis of NOAA-2 SRIR-DAY Digital count data for 24 July 1973 [24 nmi resolution; isopleths 60, 120 (enhanced), 175 (enhanced), 190].

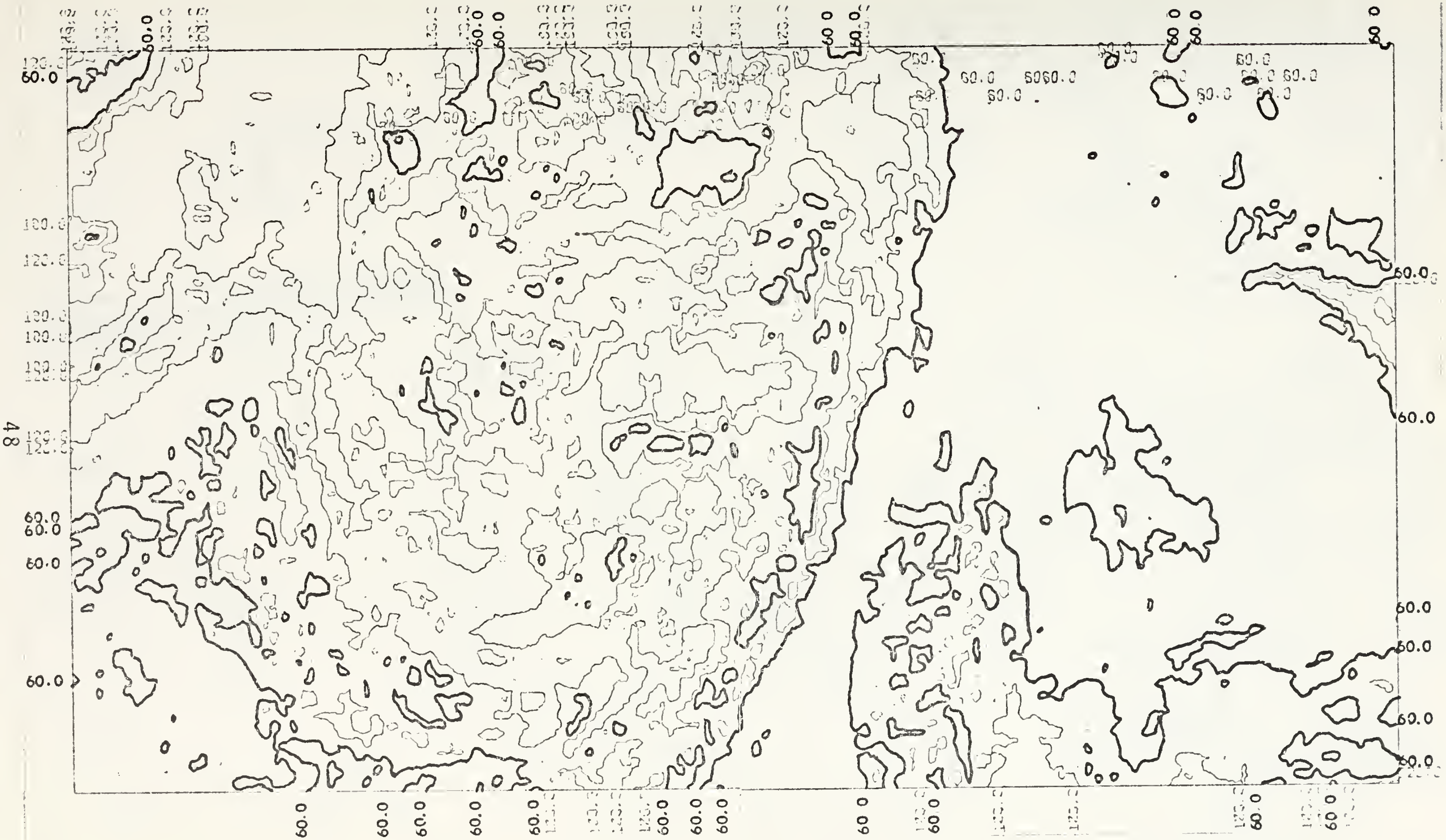

Figure 9. Analysis of NOAA-2 SRVIS digital count data for 24 July 1973 [24 nmi resolution; isopleths 60 (enhanced), 120, 180].

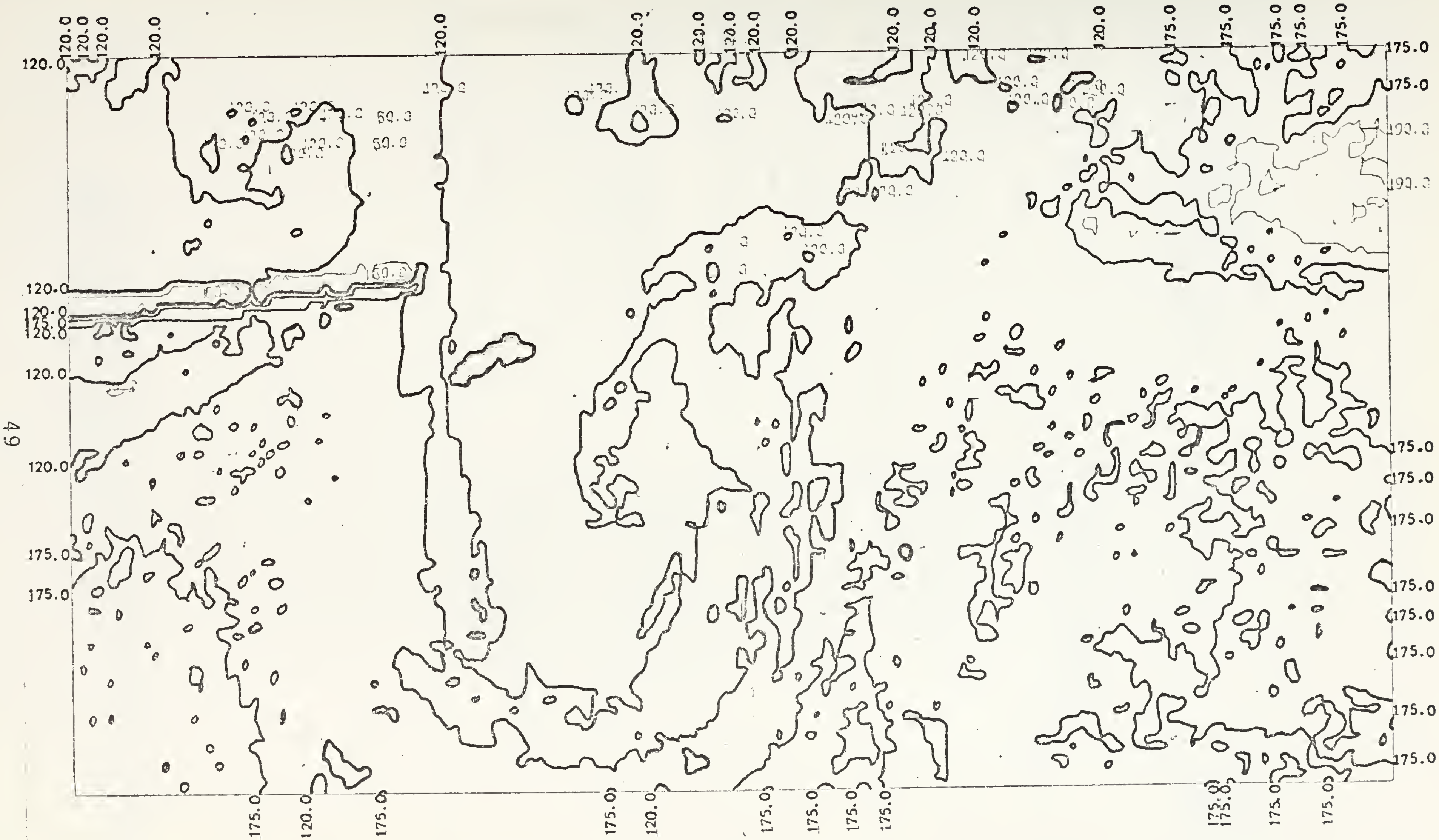

Figure 10. Analysis of NOAA-2 SRIR-NGT digital count data for 24 July 1973 [24 nmi resolution; isopleths 60, 120 (enhanced), 175 (enhanced), 190].

| Category | Code figure (ww=present weather W=past weather) | Description | Depth of fog at sea (ft) |
|---|---|---|---|
| 1 | ww=10 with or without W=4 | Light fog at station at time of observation | 33 |
| 2 | ww=11, 12 with or without W=4 | Shallow fog at station at time of observation | 33 |
| 3 | ww=28, with or without W=4 | Fog at station not at time of observation but within past hour | 33 |
| 4 | ww=40-49 with or without W=4 | Fog at a distance (40) or at the station (41-49) at time of observation | 33 |
| 5 | W=4<br>ww≠ 10,11,12,28,40-49 | Fog or thick haze or smoke within a period 1-6 hours prior to observation | ——— |

Table I. Categories used for cataloging transient-ships reporting fog-related code-figures in synoptic-time weather reports.

| Time (GMT) | Number of reports | Diagnosed / Verified | | | | | | Skill score (frontal included) | Skill score (frontal excluded) |
|---|---|---|---|---|---|---|---|---|---|
| | | Fog/fog | Fog/ no-fog | Frontal/ fog | Frontal/ no-fog | No-fog/ fog | No-fog/ no-f0g | | |
| 241800 | 68 | 9 | 13 | 2 | 20 | 1 | 23 | +0.39 | +0.38 |
| 250600 | 59 | 2 | 9 | 2 | 11 | 10 | 25 | -0.06 | -0.10 |
| 251800 | 73 | 17 | 14 | 3 | 6 | 1 | 32 | +0.47 | +0.52 |
| 260600 | 58 | 15 | 14 | 3 | 14 | 2 | 10 | +0.34 | +0.27 |
| 261800 | 65 | 22 | 14 | 0 | 7 | 4 | 18 | +0.46 | +0.39 |

Table II. Marine fog diagnosis: Verification statistics from applying qualitative guidelines to NOAA-2 imagery. Frontal/fog (Frontal/no-fog) is considered a failure (success).

| | SRIR-DAY | SRVIS | SRIR-NGT |
|---|---|---|---|
| Fog | 135-176 | 58-190 | 123-171 |
| Fog beneath frontal bands or multilevel clouds | 70-112 | 139-220 | 100-115 |

Table III. Range of NOAA-2 SRIR and SRVIS digital counts associated with verifying marine fog for the period 241800 GMT through 260600 GMT July 1973.

| Time (GMT) | Number of reports | Diagnosed / Verified | | | | | | Skill score (frontal included) | Skill score (frontal excluded) |
|---|---|---|---|---|---|---|---|---|---|
| | | Fog/fog | Fog/ no-fog | Frontal/ fog | Frontal/ no-fog | No-fog/ fog | No-fog/ no-fog | | |
| 241800 | 68 | 10 | 13 | 2 | 9 | 0 | 34 | +0.44 | +0.48 |
| 250600 | 59 | 12 | 22 | 2 | 15 | 0 | 8 | +0.25 | +0.17 |
| 251800 | 73 | 18 | 16 | 3 | 8 | 0 | 28 | +0.46 | +0.50 |
| 260600 | 58 | 18 | 16 | 2 | 11 | 0 | 11 | +0.41 | +0.35 |
| 261800 | 65 | 23 | 13 | 3 | 11 | 0 | 15 | +0.52 | +0.51 |

Table IV. Marine fog diagnosis: Verification statistics from using cut-off digital count values for processing NOAA-2 digital count data. Frontal/fog (Frontal/no-fog) is considered a failure (success).

## APPENDIX A

### QUALITATIVE GUIDELINES FOR OUTLINING AREAS OF MARINE FOG USING NOAA SRVIS, SRIR-DAY, AND SRIR-NGT IMAGERY IN CONJUNCTION WITH TRANSIENT-SHIP SYNOPTIC DATA AND SEA-LEVEL PRESSURE ANALYSES

1. Outline areas in the SRVIS and SRIR-NGT which appear cloud-free (should appear dark).
2. Outline areas in SRVIS where the cloud texture appears "bumpy" (which implies cumuliform or stratocumuliform clouds) and note the areas where clouds have a smooth texture. In SRIR-NGT, the bumpy-textured areas should appear as patches of alternating light and dark gray shades. The smooth textured clouds will appear as a nearly continuous light gray shade.
3. Outline, as well as possible, the total cloud band of frontal zones in SRVIS or SRIR-NGT (including areas with apparently multilevel clouds).
4. Observe the SRIR-DAY imagery in the areas declared as "cloud-free" in Step 1. Note the gray shade of this reference "clear-column" (for SRIR-NGT, this should have been done in Step 1).
5. Note the areas in the SRIR imagery which display smooth textured clouds (excluding frontal bands) that radiate in a dark to medium gray shade (i.e., slightly lighter than the "clear column"), and outline this area as an area of fog. If a white appearance occurs in the

medium gray shaded area, assign "no-fog" to the region under that white area.

6. Observe the portions of the frontal band along the leading and trailing edges. If there are regions with a slightly darker gray shade than the cold, multi-layered clouds of the main frontal band and slightly lighter than the clear-air masses in advance of and behind the frontal band, outline these areas as areas of fog.
7. Compare the areas designated as "fog" and "no-fog" with available transient-ship synoptic data and the current sea-level pressure analysis. Adjust the satellite-designated fog areas to be compatible with circulation/thermal features and marine observations.

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